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(54) **Method for automatically identifying and classifying defects, in particular on a semiconductor wafer**

(57) A methodology is provided for qualitatively identifying features of an article, such as defects on the surface of a semiconductor substrate, with a string of symbols, such as numbers, according to relevant defect characteristics and information relating to the processing tools visited by the wafer, including reliability information. Embodiments include generalizing, after a defect on a wafer is discovered and inspected (as by optical review, SEM, EDS, AFM, etc.), each quantitative attribute of the defect such as the defect's size, material composition, color, position on the surface of the wafer, etc. into a qualitative category, assigning a numerical symbol to each attribute for identification, and sequencing the symbols in a predetermined manner. The identification sequences of all defects are stored in a database, where they are easily compared with other correspondingly identified defects. The identification sequence also includes a number representative of the wafer's last-visited processing tool, thereby associating the defect with a tool. After the defect is investigated and determined as being caused by a particular fault of the tool, this information is stored and linked to the defect's identification sequence. Thereafter, if a similar defect occurs in another wafer, the later defect's identification sequence is matched to that of the previous defect by searching the defect database, indicating the same cause for the later defect, thereby enabling ready identification of the root causes of defects, and enabling early corrective action to be taken.

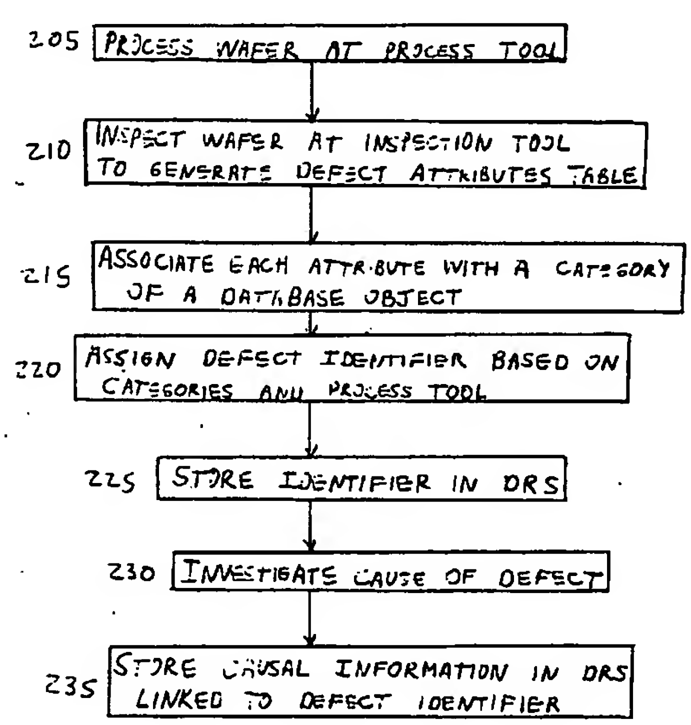

FIG. 2

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fies defects in a standardized way. There further exists a need for an inspection methodology that relates the tools visited by the wafers and reliability information of those tools to detected defects in order to readily identify the root causes of defects, thereby enabling early corrective action to be taken. This need is becoming more critical as the density of surface features, die sizes, and number of layers in devices increase, requiring the number of defects to be drastically reduced to attain an acceptable manufacturing yield.

SUMMARY OF THE INVENTION

[0010] An advantage of the present invention is the ability to identify defects in a manufactured article, such as a semiconductor wafer, in a standardized qualitative manner, thereby allowing information relating to the defect to be easily linked to the defect, stored and searched. A further advantage of the present invention is the ability to include, in the identification of a defect, information relating to its cause, thereby enabling efficient identification of process problem areas, and the relation of defect causes to corrective action.

[0011] According to the present invention, the foregoing and other advantages are achieved in part by a method of classifying a feature of an article, which method comprises determining attributes of the feature; generalizing the attributes by associating each attribute with one or more categories, each category being a subset of one of a plurality of database objects associated with the attributes; assigning each category a symbol; arranging the symbols of the categories in a predetermined sequence to form an identifier for the feature; and storing the identifier in a database.

[0012] Another aspect of the present invention is a computer-readable medium bearing instructions for executing the above steps of the present methodology.

[0013] Additional advantages of the present invention will become readily apparent to those skilled in this art from the following detailed description, wherein only the preferred embodiment of the present invention is shown and described, simply by way of illustration of the best mode contemplated for carrying out the present invention. As will be realized, the present invention is capable of other and different embodiments, and its several details are capable of modifications in various obvious respects, all without departing from the present invention. Accordingly, the drawings and description are to be regarded as illustrative in nature, and not as restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Reference is made to the attached drawings, wherein elements having the same reference numeral designations represent like elements throughout, and wherein:

Figure 1 schematically illustrates an apparatus used to implement the present invention.

Figure 2 is a flow chart illustrating sequential steps in a method according to an embodiment of the present invention.

Figure 3 is a conceptual flow chart illustrating the methodology of the present invention.

Figure 4A illustrates a database object and its subsets according to an embodiment of the present invention

Figure 4B illustrates the formation of a defect identifier according to the present invention.

Figure 5A illustrates a conventional defect map produced by an inspection tool.

Figure 5B illustrates the division of the surface of a semiconductor wafer according to an embodiment of the present invention.

Figure 6 is a flow chart illustrating sequential steps in a method according to another embodiment of the present invention.

Figures 7A-7D schematically illustrate defect analysis according to embodiments of the present invention.

Figure 8 illustrates the displayed results of a defect analysis according to the methodology of the present invention.

Figure 9 is a block diagram that illustrates an embodiment of the present invention.

DESCRIPTION OF THE INVENTION

[0015] While conventional methodologies for in-process inspection of manufactured articles, such as semiconductor wafers, identify defects, they do not identify the defects in a standardized, qualitative way, or provide information relating to the tools visited by the wafer that would lead to early positive identification of the defect sources. The present invention addresses these problems by qualitatively identifying defects with a string of symbols, such as numbers, according to relevant defect characteristics and information relating to the last-visited tool, including reliability information, thereby enabling ready identification of the root causes of defects, and enabling early corrective action to be taken.

[0016] According to certain embodiments of the present invention, after a defect on a wafer is discovered and inspected, as by optical review, SEM, EDS, AFM, etc., each quantitative attribute of the defect such as the defect's size, material composition, color, position on the surface of the wafer, etc. is generalized into a qualitative category and assigned a numerical symbol for identification. For example, a substantially round, approximately one-micron diameter particle composed of 79% aluminum is identified by a sequence of numbers in a predetermined order comprising a number representative of "aluminum" (the defect material), another number representative of "round" (the defect

"size", "composition", "color", "position on the wafer", etc., while the categories or subsets 420 of the database objects 410 allow the defect attributes to be further classified and identified as having one or more of a limited number of specific characteristics determined to be significant by the user. In this way, defect information is standardized and simplified to facilitate subsequent searching of the data.

[0024] For example, a particle defect is placed in a category 420 called "particle on a pattern" or "particle embedded in a pattern" within a database object 410 called "particle". A particle having dimensions (i.e., attributes) of one micron wide and four microns long is categorized, for example, as an oval with a 4:1 axis ratio within the "shape" database object 410, while a spherical particle is categorized as a 1:1 axis ratio within this database object. Further, as shown in Fig. 4A, a spherical particle with a diameter of 1.5 micron is, for example, categorized as spherical with a diameter between one and two microns (see "x"). If it had a diameter of 2.3 microns, it would be categorized as spherical with a diameter between 2 and 3 microns. In the same way, a particle comprising stainless steel is categorized, for example, as comprising iron (Fe), chromium (Cr), nickel (Ni) and carbon (C), thereby generalizing from a metal alloy to its elements (FE, Cr, Ni, C). Alternatively, if more detail is desired by the user, a particle comprising stainless steel is categorized as comprising iron in a "primary composition" database object, and chromium, nickel and carbon in separate "secondary composition" database objects.

[0025] In other embodiments of the present invention, attributes of a plurality of defects are generalized into a subset category of a "pattern" database object 410 from a conventional defect map. Each defect site location from a conventional defect map is treated as an x and y coordinate attribute. The defect sites are tallied by their coordinates to populate predefined "sectors" which define discrete areas on the wafer. Patterns are defined from the sector population, thereby describing the population mathematically. The methodology of this embodiment of the present invention facilitates fast and accurate pattern determination and requires no user judgement.

[0026] Referring to Figs. 5A and 5B and the flow chart of Fig. 6, a wafer is inspected in a conventional manner, typically at an optical inspection tool, to produce a defect map M having suspected defect sites D at step 600. At step 905, the wafer surface is divided into sectors, such as sectors 1-9 in Fig. 5B, which correspond to expected significant defect areas. At step 610, each defect site D is associated with one of the sectors 1-9, and a count of the number of defect sites in each sector is determined at step 615. Next, the number of defect sites in each sector 1-9 is compared to a predetermined threshold number (see step 620) or standard deviation. Then, at step 625, the defect map is treated as a defect attribute and is generalized into a subset category of a pattern database object based on the sectors 1-9 that have greater than the threshold number of defect sites.

[0027] For example, a pattern database object having 9 factorial (9!) subset categories based on sectors 1-9 of Fig. 5B is created. If the predetermined threshold number of defects sites for each sector is 25, then the defect map M of Fig. 5A is generalized as being in the category reflecting that sectors 2 and 6 contain many defect sites.

[0028] In another embodiment of the present invention wherein defect sites D of a defect map M are associated with predetermined sectors, such as sectors 1-9 of a wafer surface, a pattern database object has predetermined shape category subsets corresponding to expected significant defect site distributions. Referring now to Fig. 7A, when a significant number of defect sites are found in sector 9, the defect map is placed in a "defects at center" pattern category. In the defect map of Fig. 7B, defect sites are concentrated in sectors 1-4, so this defect map is placed in a "doughnut" shape pattern category. The doughnut shape pattern is significant because it may indicate problems with a tool, such as a vacuum chuck, visited by the wafer. Fig. 7C illustrates defect sites concentrated in sectors 5-8, as may be caused by a clamp ring, so this defect map is placed in a "ring" or "outer edge" shape pattern category.

[0029] Alternatively, conventional spatial signature analysis (SSA) can be used to analyze a pattern of defect sites, typically employing information from YMS 140. The results of SSA are then treated as another defect attribute and generalized into an appropriate subset category or categories of a pattern database object.

[0030] In still another embodiment of the present invention, as illustrated in Fig. 7D, when defect sites D of a defect map M form a random pattern, a pattern database object having predetermined fractal number subsets is used. In this embodiment, the pattern of defect sites is expressed mathematically using a conventional fractal software program, such as is available from the National Bureau of Standards. Typically, in fractal techniques, shapes of small dimensions, such as small hexagons 700, are used to fill the space within a pattern, such as within a random pattern of defect sites D. The number of hexagons 700 needed to fill the space is the pattern's "fractal number". Thus, a random pattern of defect sites is generalized by placing it into a category corresponding to its fractal number.

[0031] When each defect attribute A-K is associated with a category 420 of a database object 410 at step 215, each category of each database object is preassigned a symbol, preferably an integer or integers. This is illustrated in Fig. 4A, wherein a numerical symbol 430 is associated with each category 420 of a database object 410. The "x" represents a defect attribute that has been categorized. At step 220, after all the attributes of a defect are categorized, the defect is

906. Transmission media include coaxial cable, copper wire and fiber optics, including the wires that comprise bus 902. Transmission media can also take the form of acoustic or light waves, such as those generated during radio frequency (RF) and infrared (IR) data communications. Common forms of computer-readable media include, for example, a floppy disk, a flexible disk, hard disk, magnetic tape, any other magnetic medium, a CD-ROM, DVD, any other optical medium, punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a PROM, and EPROM, a FLASH-EPROM, any other memory chip or cartridge, or any other medium from which a computer can read.

[0039] Various forms of computer-readable media may be involved in carrying out one or more sequences of one or more instructions to CPU 904 for execution. For example, the instructions may initially be borne on a magnetic disk of a remote computer. The remote computer can load the instructions into its dynamic memory and send the instructions over a telephone line using a modem. A modem local to processor 100 can receive the data on the telephone line and use an infrared transmitter to convert the data to an infrared signal. An infrared detector coupled to bus 902 can receive the data carried in the infrared signal and place the data on bus 902. Bus 902 carries the data to main memory 906, from which CPU 904 retrieves and executes the instructions. The instructions received by main memory 906 may optionally be stored on storage device 910 either before or after execution by CPU 904.

[0040] The inventive methodology provides for in-process inspection of semiconductor wafers that quickly identifies defects in a standardized way using information gathered by conventional inspection techniques. Furthermore, the present invention relates the process tools visited by the wafers and reliability information of those tools to detected defects in order to readily identify the root causes of defects, thereby enabling early corrective action to be taken. Thus, the present invention contributes to the maintenance of high production throughput and increases manufacturing yield as design rules shrink. The present invention is applicable to the inspection of any semiconductor wafer, and is especially useful for in-process inspection of semiconductor wafers during manufacture of high density semiconductor devices with submicron design features.

[0041] The present invention can be practiced by employing conventional materials, methodology and equipment. Accordingly, the details of such materials, equipment and methodology are not set forth herein in detail. In the previous descriptions, numerous specific details are set forth, such as specific materials, structures, chemicals, processes, etc., in order to provide a thorough understanding of the present invention. However, it should be recognized that the present invention can be practiced without resorting to the details specifically set forth. In other instances, well known processing structures have not been described in detail, in order not to unnecessarily obscure the present invention.

[0042] Only the preferred embodiment of the present invention and but a few examples of its versatility are shown and described in the present disclosure. It is to be understood that the present invention is capable of use in various other combinations and environments and is capable of changes or modifications within the scope of the inventive concept as expressed herein.

Claims

1. A method of classifying a feature of an article, which method comprises:

    (a) determining attributes of the feature;
    (b) generalizing the attributes by associating each attribute with one or more categories, each category being a subset of one of a plurality of database objects associated with the attributes;
    (c) assigning each category a symbol;
    (d) arranging the symbols of the categories in a predetermined sequence to form an identifier for the feature; and
    (e) storing the identifier in a database.

2. The method according to claim 1, comprising inspecting the article using an inspection tool to determine the attributes.

3. The method of claim 2, comprising:

    performing a processing step on the article using a processing tool prior to inspecting the article;
    assigning the processing tool one of the symbols as an identifier for the processing tool; and
    including the processing tool symbol in the sequence.

4. The method of claim 3, wherein the processing step is performed using a set of process parameters, the method comprising:

    storing the process parameters; and
    linking the process parameters and the identifier.

5. The method according to any preceding claim, wherein the feature comprises a plurality of defects on a surface of the article, the method comprising generalizing the plurality of defects as a pattern database object having a predetermined shape category subset.

6. The method according to any of claims 1 to 4, wherein the feature comprises a plurality of defects on a surface of the article, the method comprising

one of claims 14 to 17, wherein the feature comprises a plurality of defects on a surface of the article, wherein the instructions, when executed, are arranged to cause the one or more processors to perform the step of generalizing the plurality of defects as a pattern database object having a predetermined shape category subset.

19. The computer-readable medium according to any one of claims 14 to 17, wherein the feature comprises a plurality of defects on a surface of the article, wherein the instructions, when executed, are arranged to cause the one or more processors to perform the step of generalizing the plurality of defects as a pattern database object having a predetermined location on the surface category subset.

20. The computer-readable medium according to claim 15, wherein the article is a semiconductor substrate and the feature comprises a plurality of defects on a surface of the semiconductor substrate, wherein the instructions, when executed, are arranged to cause the one or more processors to perform the step of receiving the feature attributes from at least one of an optical inspection station, a wafer inspection station, a scanning electron microscope (SEM), an atomic force microscope (AFM), energy dispersive spectroscopy (EDS), or electron spectroscopy for chemical analysis (ESCA).

21. The computer-readable medium according to any of claims 15 to 20, wherein the article is a semiconductor substrate and the feature comprises a plurality of defects on a surface of the semiconductor substrate, wherein the instructions, when executed, are arranged to cause the one or more processors to perform the steps of:

receiving a defect map of a plurality of defects from the inspection tool, such that the attributes of each defect comprise a set of coordinates corresponding to its location on a surface of the substrate;
dividing the substrate into sectors;
associating each defect with one of the sectors based on its coordinates;
counting the defects in each sector;
comparing the number of defects in each sector to a predetermined threshold number; and
associating the defects in a first one of the sectors with a category of a pattern database object that includes the first sector, when the number of defects in the first sector is greater than or equal to the predetermined threshold number.

22. The computer-readable medium according to claim 14, wherein the feature comprises a plurality of defects on a surface of the article, wherein the instructions, when executed, are arranged to cause the one or more processors to perform the step of generalizing the plurality of defects as a pattern database object having a predetermined fractal number subset.

23. The computer-readable medium according to any of claims 14 to 22, wherein the instructions, when executed, are arranged to cause the one or more processors to perform the step of assigning integers as the symbols.

24. The computer-readable medium according to claim 16, wherein the feature comprises a defect in the article, wherein a cause of the defect is determined and stored, wherein the cause is related to the processing tool, and wherein the instructions, when executed, are arranged to cause the one or more processors to perform the step of linking the cause and the identifier.

25. The computer-readable medium according to any of claims 14 to 24, wherein the instructions, when executed, are arranged to cause the one or more processors to perform the steps of:

repeating steps (a)-(e) for a plurality of features; and
searching for corresponding identifiers based on one or more corresponding symbols of the identifiers in the database.

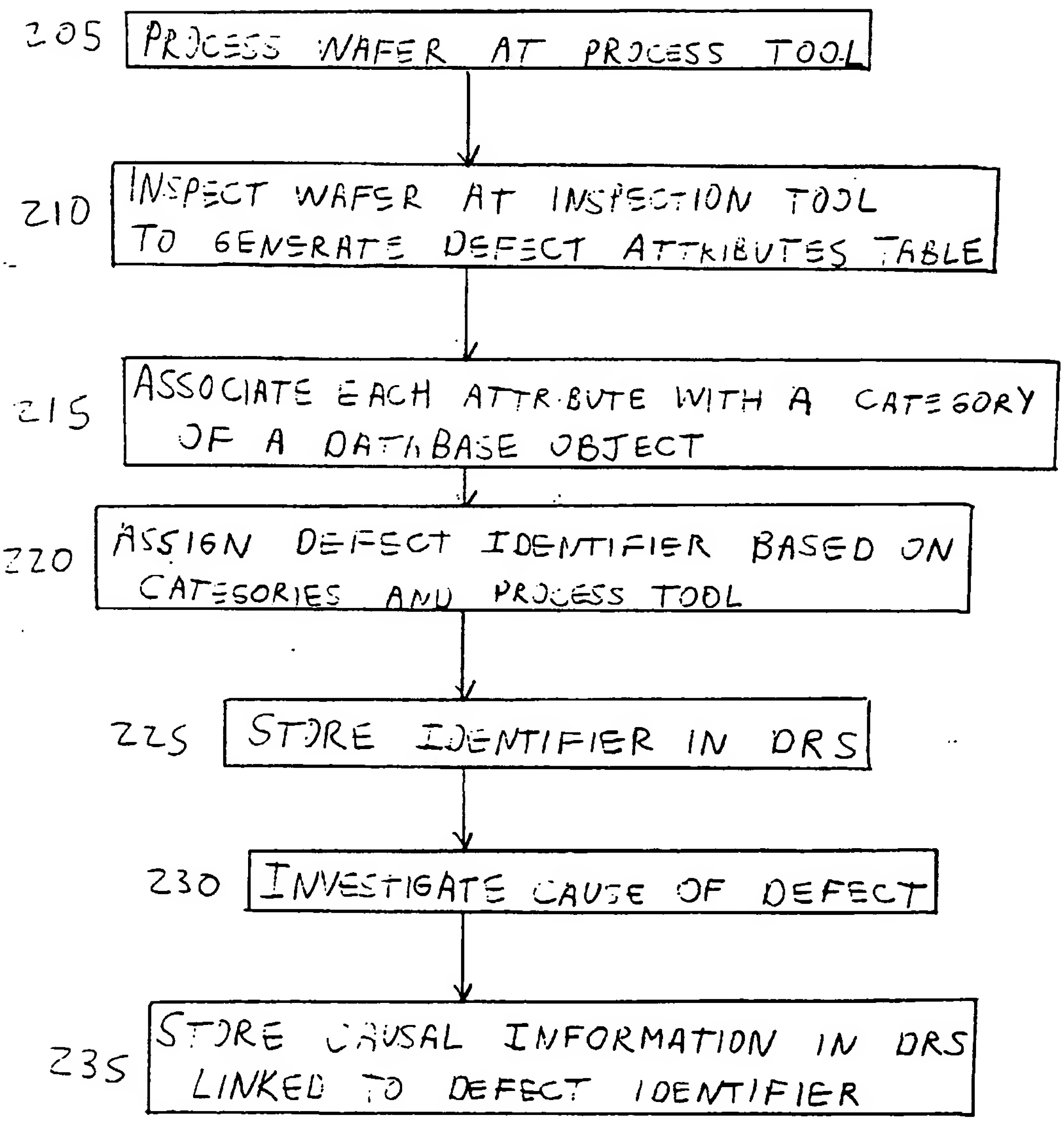
205
PROCESS WAFER AT PROCESS TOOL
210
INSPECT WAFER AT INSPECTION TOOL TO GENERATE DEFECT ATTRIBUTES TABLE
215
ASSOCIATE EACH ATTRIBUTE WITH A CATEGORY OF A DATABASE OBJECT
220
ASSIGN DEFECT IDENTIFIER BASED ON CATEGORIES AND PROCESS TOOL
225
STORE IDENTIFIER IN DRS
230
INVESTIGATE CAUSE OF DEFECT
235
STORE CAUSAL INFORMATION IN DRS LINKED TO DEFECT IDENTIFIER

FIG. 2

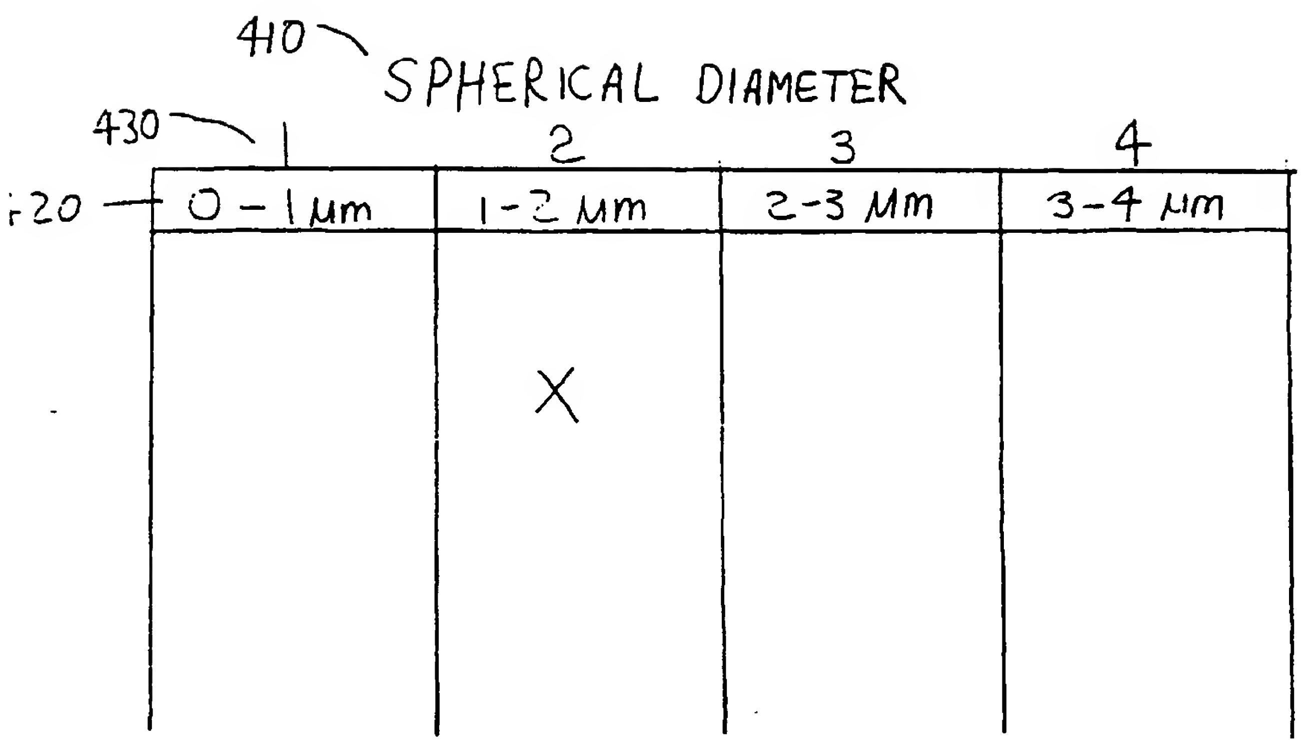
410
SPHERICAL DIAMETER
430
1
2
3
4
420
0 - 1 μm
1-2 μm
2-3 μm
3-4 μm
X

FIG. 4A

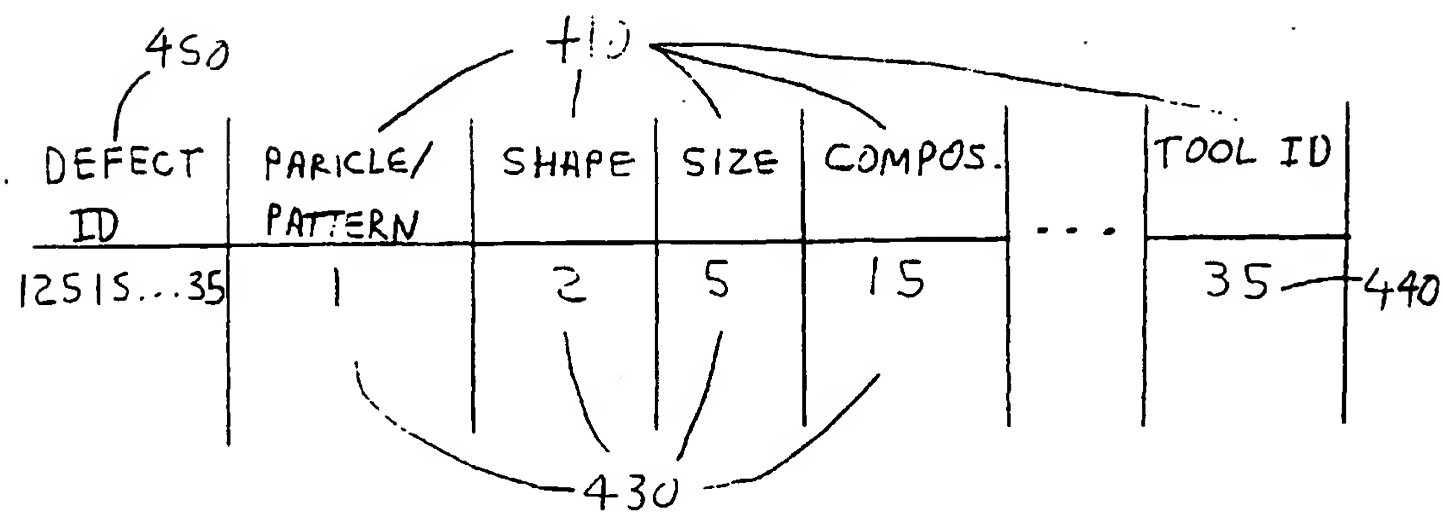
450
410
DEFECT ID
PARICLE/ PATTERN
SHAPE
SIZE
COMPOS.
...
TOOL ID
12515...35
1
2
5
15
35
440
430

FIG. 4B

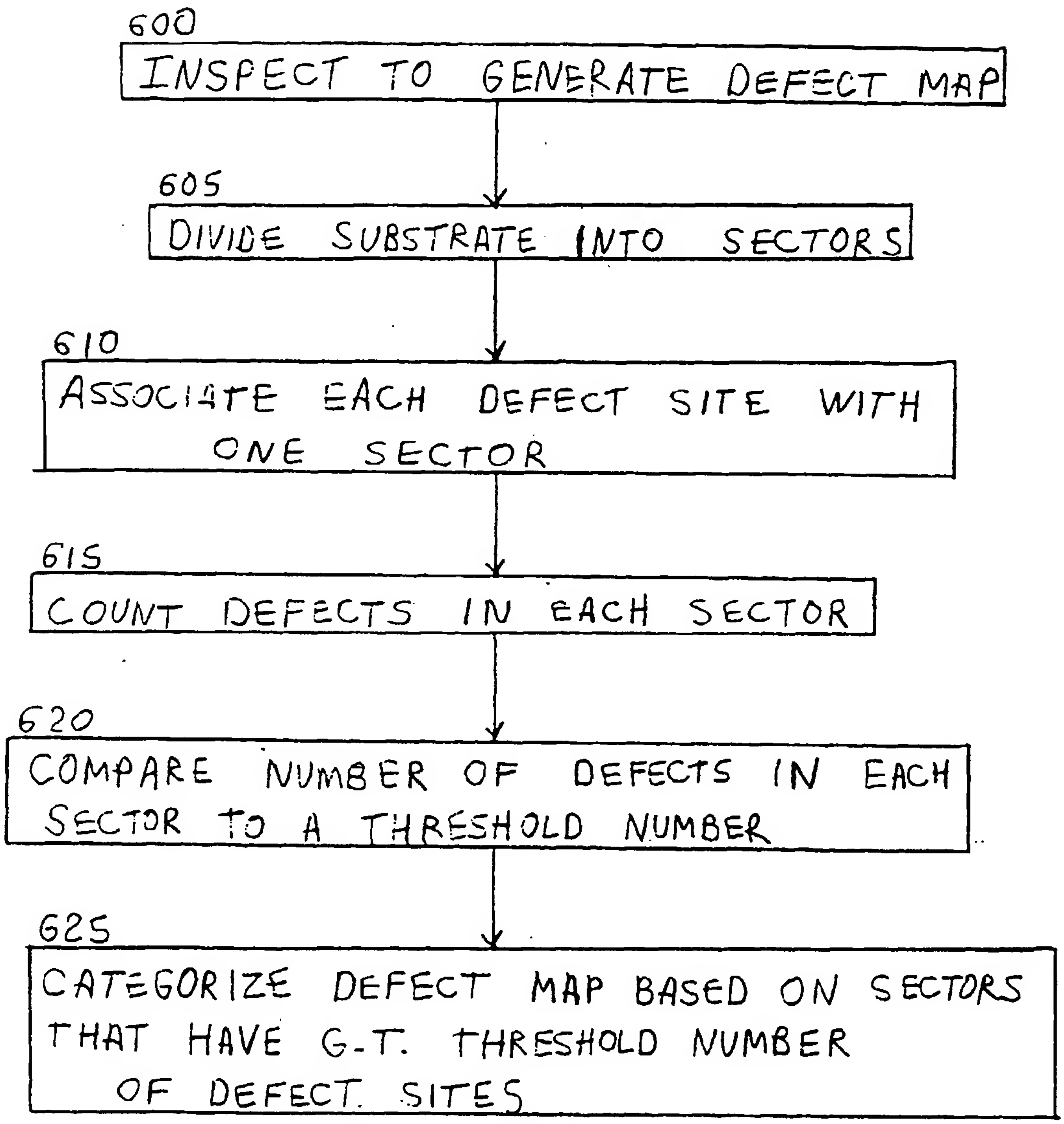
600
INSPECT TO GENERATE DEFECT MAP
605
DIVIDE SUBSTRATE INTO SECTORS
610
ASSOCIATE EACH DEFECT SITE WITH ONE SECTOR
615
COUNT DEFECTS IN EACH SECTOR
620
COMPARE NUMBER OF DEFECTS IN EACH SECTOR TO A THRESHOLD NUMBER
625
CATEGORIZE DEFECT MAP BASED ON SECTORS THAT HAVE G-T. THRESHOLD NUMBER OF DEFECT SITES

FIG. 6

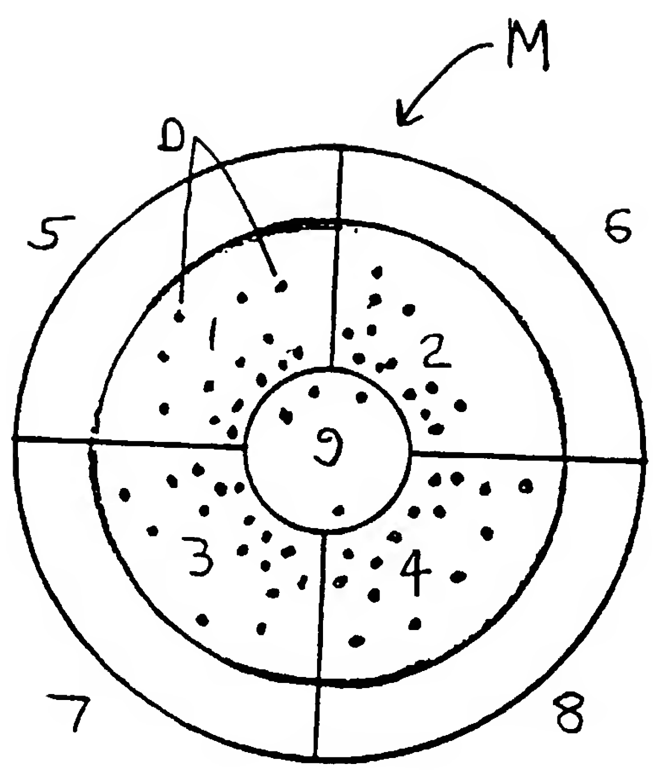

FIG. 7B

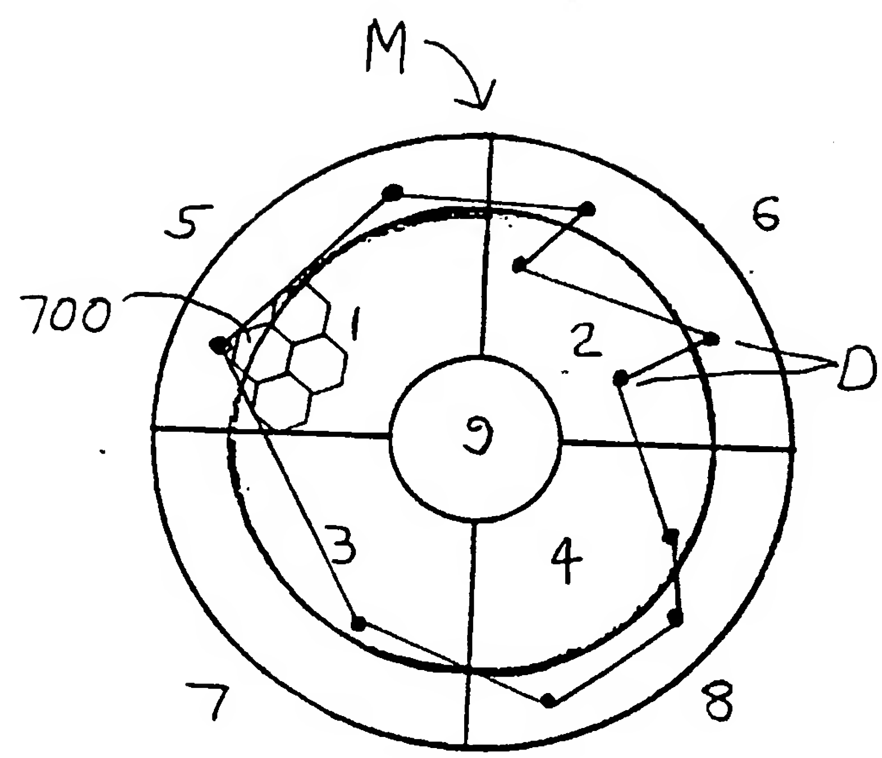

FIG. 7D

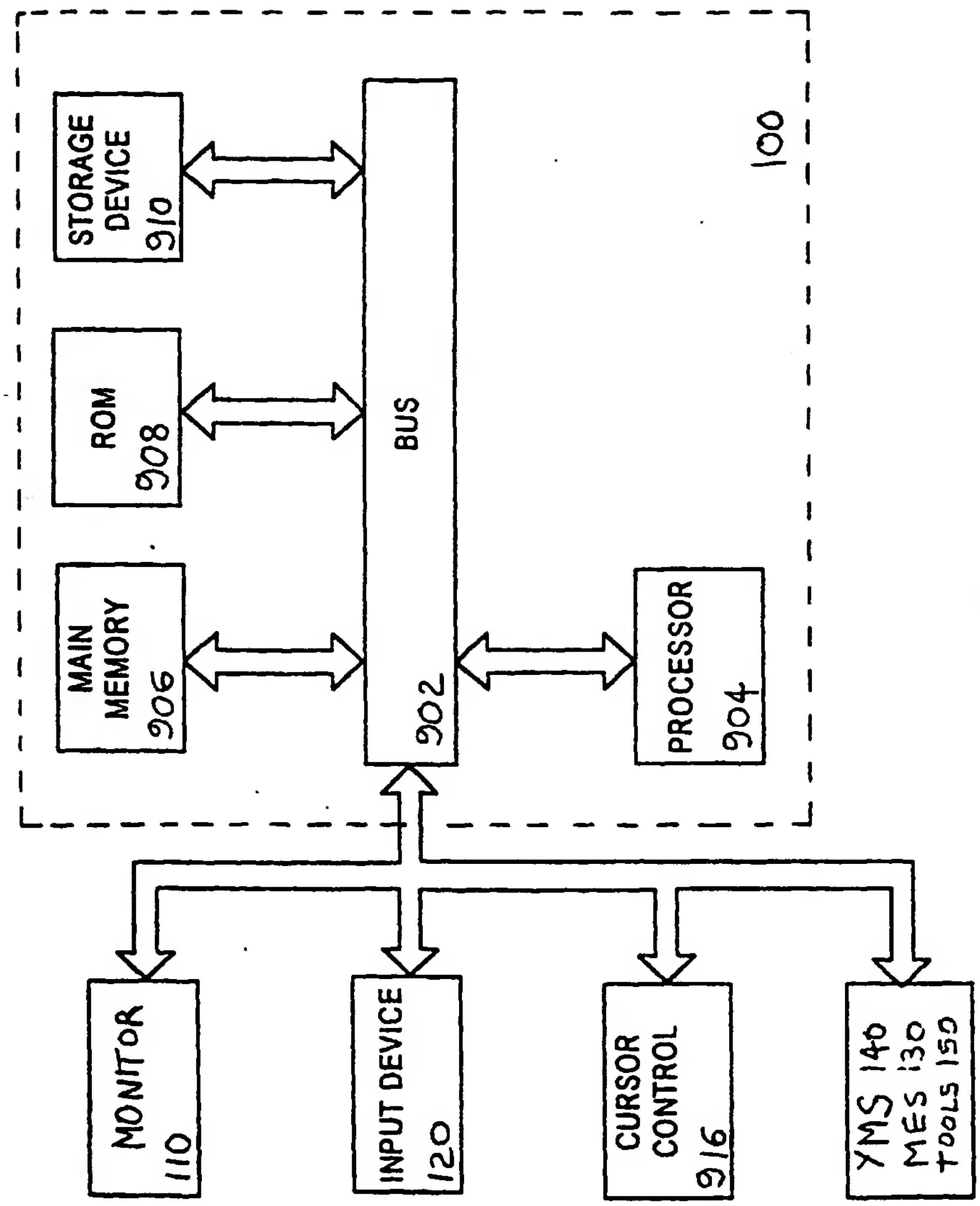
STORAGE DEVICE 910
ROM 908
MAIN MEMORY 906
BUS
902
PROCESSOR 904
100
MONITOR 110
INPUT DEVICE 120
CURSOR CONTROL 916
YMS 140
MES 130
TOOLS 150

FIG. 9